

Regular black hole remnants and graviatoms with de Sitter interior as heavy dark matter candidates probing inhomogeneity of early Universe

Irina Dymnikova^{1,2} and Maxim Khlopov^{3,4,5}

¹ *Department of Mathematics and Computer Science, University of Warmia and Mazury, Słoneczna 54, 10-710 Olsztyn, Poland; e-mail: irina@matman.uwm.edu.pl*

² *A.F. Ioffe Physico-Technical Institute, Politekhnicheskaja 26, St.Petersburg, 194021 Russia*

³ *APC laboratory 10, rue Alice Domon et Léonie Duquet
75205 Paris Cedex 13, France*

⁴ *Centre for Cosmoparticle Physics "Cosmion"*

⁵ *National Research Nuclear University "MEPhI"
(Moscow Engineering physics Institute), 115409 Moscow, Russia*

Abstract

We address the question of regular primordial black holes with de Sitter interior, their remnants and gravitational vacuum solitons G-lumps as heavy dark matter candidates providing signatures for inhomogeneity of early Universe, which is severely constrained by the condition that the contribution of these objects in the modern density doesn't exceed the total density of dark matter. Primordial black holes and their remnants seem to be most elusive among dark matter candidates. However, we reveal a nontrivial property of compact objects with de Sitter interior to induce proton decay or decay of neutrons in neutron stars. The point is that they can form graviatoms, binding electrically charged particles. Their observational signatures as dark matter candidates provide also signatures for inhomogeneity of the early Universe. In graviatoms the cross section of the induced proton decay is strongly enhanced, what provides the possibility of their experimental searches. We predict proton decay paths induced by graviatoms in the matter as an observational signature for heavy dark matter searches at the IceCUBE experiment.

Journal Reference: *Int. J. Mod. Phys. D Vol. 24, 1545002 (2015),
special issue "Composite dark matter"*

1 Introduction

Cosmological dark matter should consist of stable particles. In the literature there are considered various alternatives to the popular candidate of weakly interacting massive point-like particles [1, 2]. It includes primordial black hole which are considered as a reliable source of dark matter for more than two decades [3, 4, 5] (for a review [6, 7, 8]).

There are several mechanisms for primordial black hole (PBH) formation [7, 8]. PBHs with the mass exceeding 10^{15} g should survive to the present time and manifest themselves as a specific form of dark matter. If the mass of PBHs is less, than 10^{15} g, they should evaporate according to the mechanism of Hawking and their effect in the dark matter is possible only if there are stable remnants of their evaporation.

Characteristic scales for astrophysical structures originated from primordial quantum black holes has been considered in [9]. The existence of black hole remnants was addressed in various aspects since PBHs were predicted in [10, 11]. For example, hybrid inflation can in principle yield the necessary abundance of primordial black hole remnants for them to be the primary

source of dark matter [4, 12]. Production of primordial black hole remnants in the early universe can induce a matter-dominated era before the onset of inflation. Effects of such an epoch on the CMB power spectrum are discussed in [13] where it was shown that they can be able to explain the quadrupole anomaly of the CMB power spectrum. Observational scheme for detection of remnants and their cosmological constraints are discussed in [14].

In the framework of low scale gravity possible signatures of black hole events in pp collisions at the CERN LHC have been investigated in the hypothesis that black holes do not decay completely into SM particles [15] but leave behind a (meta-)stable remnant [16]. The production of black hole remnants has been predicted to occur with the rate of 10^8 per year [17]. Possible signatures of black hole events have been considered. The results for the hypothesis of a stable remnant show that stable remnant scenarios up to $M_G \leq 2 \text{ TeV}$ can be already probed with the 5 fb^{-1} of integrated luminosity collected by the LHC during the last year of data taking [18]. Dark matter production at CERN LHC from black hole remnants was considered in [19].

Let us note that the end-point of black hole evaporation still remains an open issue [20, 21, 22]. In the case of a singular black hole Generalized Uncertainty Principle requires existence of a black hole remnant as a Planck size black hole [23, 24, 25]. Arguments for remnants based on the nature of the Hawking evaporation and relevant causal domains are presented in [26]. In the Palatini framework a stable remnant with the Planckian mass can arise as a geon-like solitonic object supported by the gravitational and electromagnetic field [27]. On the other hand, no evident symmetry or quantum number was found which would prevent complete evaporation [28]. Analysis of the process of evaporation in the course of formation of a black hole shows that the end-point depends essentially on the details of a collapse [29]. Character and scale of uncertainty concerning an endpoint of the Hawking evaporation of a singular black hole, are clearly evident in the case of a multihorizon spacetime ([30] and references therein). Complete evaporation of a black hole in de Sitter space creates the problem clearly formulated by Aros [31]: In the Schwarzschild-de Sitter space-time the cosmological horizon is not observer-dependent as in the de Sitter space, but real horizon due to presence of the black hole which breaks the global symmetries involving the radial direction. A serious doubt concerns a causal structure of space-time: the fate of energy radiated once a black hole disappears leaving behind the de Sitter space with nothing beyond the cosmological horizon but the de Sitter space itself, so energy can not be hidden there [31]. Complete evaporation would create one more serious problem – how to evaporate a singularity? [30].

In this paper we consider the regular primordial black hole (RPBH) remnants and gravitational solitons with de Sitter interior as heavy dark matter candidates testifying for the inhomogeneity of early Universe. The pronounced signature for its inhomogeneity is just black hole formation. In the case of regular black holes their evaporation leaves behind stable remnants [32, 33, 34], whose contribution is constrained by the observed dark matter density. RPBH and gravitational solitons with de Sitter interior can arise in a quantum collapse of primordial fluctuations in the wide range of masses including those sufficiently small to evaporate to remnants to the end of inflation [35]. Regular stable remnants with de Sitter interior should appear in the result of evaporation of a regular black hole of any origin, provided that the source term satisfies the condition $T_0^0 = T_1^1$ ($p_r = -\rho$) [36, 32, 37, 38]. They represent dark matter generically related to dark energy through de Sitter interior where $p = -\rho$, actually dark ingredients in one drop [33, 39]. They can form graviatoms with charged particles whose observational signatures as dark matter candidates provide also signatures for inhomogeneity of the early Universe.

The paper is organized as follows. In Sect.2 we present compact objects with de Sitter

interior and mechanisms of their production in the early Universe. In Sect.3 we analyze their observational signatures and in Sect.4 we summarize and discuss the results.

2 Regular black holes and solitons with de Sitter interior

The Einstein equations admit the class of regular solutions asymptotically de Sitter at the center [37, 38] with a source term specified by $T_0^0 = T_1^1$ [36], satisfying the weak energy condition, and identified as a vacuum dark fluid [33]. Solutions from this class, describe a cosmological vacuum dark energy evolving from $T_i^k = \Lambda \delta_i^k$ as $r \rightarrow 0$ to $T_i^k = \lambda \delta_i^k$ as $r \rightarrow \infty$ with $\lambda < \Lambda$ [40, 41, 42], and compact vacuum objects representing dark matter generically related to dark energy via de Sitter interior [36, 33, 39]. In the Universe with non-zero background cosmological constant λ (vacuum dark energy) dark matter is represented by regular cosmological black holes [43], their remnants [34], and vacuum gravitational solitons G-lumps [32, 38]. These compact objects can originate in the early universe in a way similar to inflation induced (singular) Planck-size black hole remnants [44] and primordial black holes [45].

A regular compact object with de Sitter interior in de Sitter space is described by the line element

$$ds^2 = g(r)dt^2 - \frac{dr^2}{g(r)} - r^2 d\Omega^2 \quad (1)$$

with the metric function [43], asymptotically de Sitter as $r = 0$ and asymptotically Schwarzschild-de Sitter as $r \rightarrow \infty$

$$g(r) = 1 - \frac{2GM(r)}{r} - \frac{\lambda}{3}r^2; \quad \mathcal{M}(r) = 4\pi \int_0^r \rho(x)x^2 dx \quad (2)$$

Spacetime has maximum three horizons [40], shown in Fig.1, an internal horizon r_a , a black hole horizon r_b , and a cosmological horizon r_c . All three horizons, r_h , evaporate with the

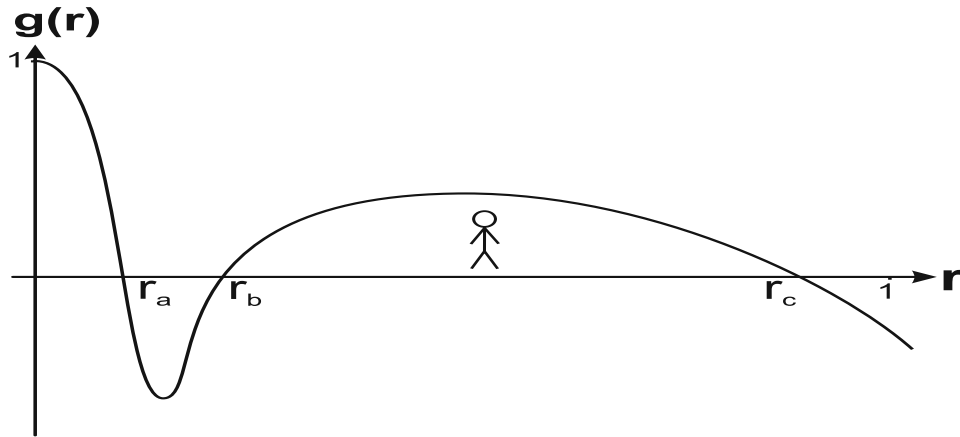


Figure 1: Typical behavior of a metric function for three-horizons spacetime [40].

Gibbons-Hawking temperature [46]

$$kT_h = \frac{\hbar c}{4\pi} |g'(r_h)| \quad (3)$$

Dynamics of horizons evaporation determines evolution of a black hole [34]. In the course of evaporation a black hole horizon shrinks while horizons r_a and r_c move outwards, and mass of black hole $m = 4\pi \int_0^\infty \rho(r)r^2 dr$ decreases (for a review [47]). Dependence of the temperature of a black hole horizon on the horizon radius, as measured by an observer (shown in Fig.1) in the R-region between the horizons r_b and r_c , is shown in Fig.2, where we plotted [47] $T_b = kT/(\hbar c/4\pi)$ on the event horizon radius $r = r_b$ normalized to $r_\lambda = \sqrt{3/\lambda}$, for the case $\sqrt{\Lambda/\lambda} = 50$.

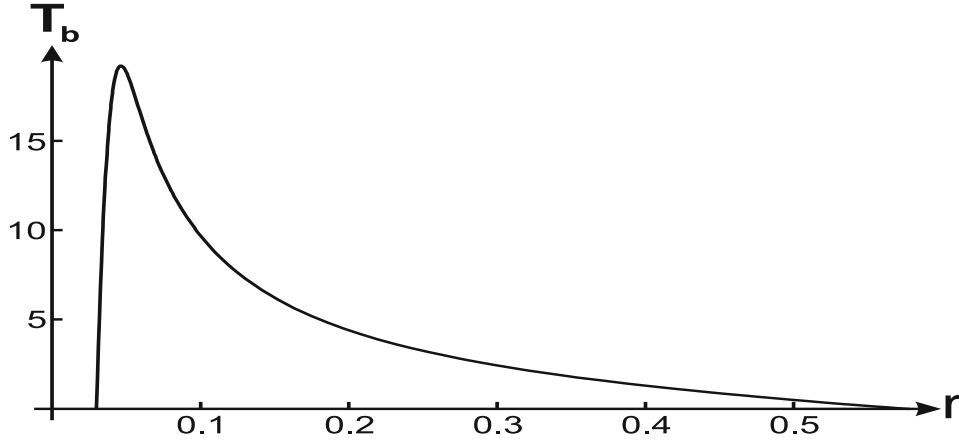


Figure 2: Temperature on a black hole horizon.

This curve is generic for a regular cosmological black hole with de Sitter interior and dictated by its two de Sitter asymptotics, in the centre and at infinity [34]: Temperature is zero at the double horizon $r_b = r_c$ (corresponding to the regular modification of the Nariai solution), grows along the branch with the negative specific heat when black hole horizon shrinks, achieves its maximum value T_{max} where specific heat breaks and changes sign which testifies for second-order phase transition, after that temperature quickly vanishes at a certain critical value m_{cr} corresponding to the double horizon $r_a = r_b$ with the positive specific heat [32, 34].

The fate of a regular black hole is thus unambiguous: it leaves behind a thermodynamically stable double-horizon remnant with zero temperature and positive specific heat [32, 34].

Solutions with $m < m_{cr}$ describe gravitational solitons without black hole horizons [32] called G-lumps since they hold themselves together by their own gravity [38].

For the density profile $\rho = \rho_{int} \exp(-r^3/r_0^2 r_g)$ [36] representing semiclassically vacuum polarization effects [32], critical mass and maximum temperature are given by

$$m_{cr} = 0.3m_{pl}\sqrt{\rho_{pl}/\rho_{int}} \quad T_{max} = 0.2T_{pl}\sqrt{\rho_{int}/\rho_{pl}} \quad (4)$$

Here ρ_{int} is the density of interior de Sitter vacuum, $r_0^2 = 3/8\pi G\rho_{int}$, and $r_g = 2Gm$.

Most general mechanism of PBH formation in the early Universe involves primordial density inhomogeneities leading to appearance of the overdense regions which can stop expansion and collapse [10, 11]. Primordial black holes can form on different stages in the early Universe provided that mass contained under its gravitational radius is sufficient for a collapse into a black hole [8, 48]. Regular primordial black holes with de Sitter interior appear when a quantum collapse of a primordial fluctuation does not lead to formation of a central singularity but stops at achieving, for a certain high density, the state $p = -\rho$ ([35] and references therein).

In the frame of the hypothesis of arising of interior de Sitter vacuum due to symmetry restoration in a collapse at the GUT scale [49], $\rho_{int} = \rho_{GUT}$ and $E_{int} = E_{GUT} \simeq 10^{15} GeV$, mass of the remnant, its gravitational radius and maximum temperature are [32, 34]

$$m_{cr} \simeq 0.6 \times 10^3 \text{ g}, \quad r_g \simeq 10^{-25} \text{ cm}, \quad T_{max} \simeq 0.2 \times 10^{11} \text{ GeV} \quad (5)$$

In the frame of hypothesis of self-regulation of geometry due to vacuum polarization effects near the Planck scale [50] or the existence of the limiting curvature of the Planck scale [51], $E_{int} = E_{Pl}$, mass of the remnant is of order of m_{Pl} and $T_{max} \simeq 0.2 T_{Pl}$.

Based on the arguments, given above, we consider existence of such stable remnants as an inevitable final stage of evaporation of RPBHs generically related to vacuum dark energy via de Sitter interior.

Probability of formation of a compact object with mass m and de Sitter interior in a quantum collapse of a quantum fluctuation at a phase transition involving an inflationary vacuum of the scale E_0 , is estimated as [35]

$$D > \exp \left[-4 \left(\frac{m}{m_{Pl}} \right)^{3/4} \left(\frac{E_{Pl}}{E_0} \right) \right] \quad (6)$$

General constraint on the mass of an object m involves the scale of the interior de Sitter vacuum and reads [35]

$$\frac{m}{m_{Pl}} > \left(\frac{E_0}{E_{Pl}} \right)^4 \left(\frac{E_{Pl}}{E_{int}} \right)^8 \quad (7)$$

In the case of the GUT scale for both inflationary and interior de Sitter vacuum, $E_{int} = E_0 = E_{GUT} \simeq 10^{15} GeV$, it gives the constraint $m > 10^{11} \text{ g}$. RPBHs arising in a quantum collapse of primordial quantum fluctuations, have enough time to evaporate producing stable remnants.

In the case of interior de Sitter vacuum of the Planck scale, $E_{int} = E_{Pl}$, mass range (7) of compact objects emerging from a collapse, admits also G-lumps which have been produced with the bigger probability by virtue of (6).

One more possibility of production of RPBH and solitons G-lumps from quantum collapse of quantum fluctuations can be realized at the second inflationary stage predicted by the standard model of particle physics as related to a phase transition at the QCD scale $E_0 \simeq 100 - 200 MeV$ ([52] and references therein). At this stage quite massive remnants and solitons with $m \leq m_{cr}$ given by (4) could be produced although with smaller probability by virtue of (6).

Another mechanism of production of compact objects with the de Sitter interior can work at the first-order phase transitions. They can form in collisions of true vacuum bubbles arising in a false vacuum background, then a false vacuum of the background scale E_0 appears inside an object as E_{int} captured in a collision [53, 54, 55].

Regular primordial black holes, their remnants and G-lumps can form graviatoms, i.e., gravitationally bound quantum systems made of such an object as a nucleus and a captured charged particle ([35] and references therein). RPBH and G-lumps arising at the first and second inflationary stages capture available particles. At the end of the first inflationary stage GUT particles can be captured, whose binding energy in graviatoms is comparable with their mass (which makes graviatoms stable), and survive to the present epoch as constituents of graviatoms [35]. Electromagnetic radiation of the graviatom can bear information about a fundamental symmetry scale of its interior de Sitter vacuum and serve as its observational signature. Characteristic frequency of the oscillatory type radiation of graviatom is $\hbar\omega =$

$0.678(\hbar c/r_{int})$ where r_{int} is the de Sitter radius $r_{int}^2 = 3c^2/8\pi G\rho_{int}$. It gives $\hbar\omega = 0.678 \times 10^{11}\text{GeV}(E_{int}/E_{GUT})^2$ [35]. Current experiments allow detection of photons up to $10^{11.5}$ GeV [56] so that radiation falls within the range of observational possibilities for graviatoms with the GUT scale de Sitter interior.

3 Observational signatures

The concentration of stable remnants of RPBHs is restricted by the condition that their modern contribution into the total density doesn't exceed the total density of dark matter.

Consider, for simplicity, the case, when RPBH of mass $m \geq m_{cr}$ is formed in the early Universe on the stage of relativistic expansion with the equation of state $p = \epsilon/3$ at the time $t_i(m) = m/m_{pl}^2$ and evaporates on radiation dominance (RD) stage at $t_e(m) = m^3/m_{pl}^4$. If the fraction of the total cosmological density in the period of PBH formation was $\beta(m)$, this contribution grew at the RD stage inversely proportional to the scale factor $\propto (t/t_i)^{1/2}$ and reached $\alpha(m) = (t_e(m)/t_i(m))^{1/2}\beta(m) = (m/m_{pl})\beta(m)$ in the period of evaporation.

Since the evaporation of PBHs with mass $m \geq m_{cr}$ ends by formation of remnant with mass m_{cr} , these remnants contribute into the total density after evaporation as

$$\beta(m, m_{cr}) = \frac{m_{cr}}{m_{pl}}\beta(m).$$

For PBHs, evaporating before the end RD stage at t_{rd} , the contribution of remnants into the total density grows $\propto (t/t_e)^{1/2}$ and becomes equal to

$$\alpha_{rd} = \left(\frac{t_{rd}}{t_e(m)}\right)^{1/2} \frac{m_{cr}}{m_{pl}}\beta(m) = \left(\frac{t_{rd}}{t_{pl}}\right)^{1/2} \left(\frac{m_{pl}}{m}\right)^{1/2} \frac{m_{cr}}{m}\beta(m)$$

at $t = t_{rd}$.

The condition $\alpha_{rd} \leq 1$ that this contribution doesn't exceed the total dark matter density in the period of matter dominance after the end of RD stage at $t = t_{rd}$ results in the following constraint on the fraction $\beta(m)$ of the total density, corresponding to PBHs with mass $m \geq m_{cr}$ in the period of their formation

$$\beta(m) \leq \left(\frac{t_{pl}}{t_{rd}}\right)^{1/2} \left(\frac{m}{m_{pl}}\right)^{1/2} \frac{m}{m_{cr}}. \quad (8)$$

It provides a strong nontrivial constraint on $\beta(m)$ for PBHs with mass $m < 10^9 g$, which evaporate before the era of Big Bang Nucleosynthesis and for which the model independent constraint from the observed entropy of the Universe is rather weak.

The constraint Eq.(8) is the strongest, when the mass of evaporating PBHs is close to its minimal possible value, corresponding to the mass of the stable remnant. In this case the restriction Eq.(8) reads as

$$\beta(m_{cr}) \leq \left(\frac{t_{pl}}{t_{rd}}\right)^{1/2} \left(\frac{m_{cr}}{m_{pl}}\right)^{1/2} \approx 10^{-24}, \quad (9)$$

where the numerical estimation is given for $m_{cr} \simeq 0.6 \times 10^3$ g, $t_{pl} = 5 \cdot 10^{-44}$ s, $t_{rd} = 5 \cdot 10^{12}$ s and $m_{pl} \simeq 2 \times 10^{-5}$ g.

It should be noted that the constraint Eq.(8) can become weaker with the account for possible existence of early dust-like stages, at which the contribution of PBHs into the total density doesn't grow. However, on the other hand, the probability of PBH formation at such stages can grow and in any case, even weakened, the constraint Eq.(8) still remains much stronger than the one from the entropy of the Universe. One should also take into account that stronger constraints on miniPBHs existing in the literature assume the existence of stable hypothetical particles, like moduli [57] or gravitino [58], while the constraint obtained in the present work is based on the existence of stable remnants only and is thus independent of particle physics models.

The case of strict equality in the Eq.(8) corresponds to the dominance of remnants in the dark matter density. This form of dark matter may be the most elusive in the list of dark matter candidates, owing to a very small cross section of their interaction with matter and between themselves.

Indeed, geometrical cross section of these objects is of the order of $\sigma_g \simeq \pi r_g^2 \simeq 3 \cdot 10^{-50} \text{ cm}^2$. This value can be compared with the sensitivity of direct WIMP searches in the underground detectors, which is expected in the planned most sensitive XENON1T detector to be $\sigma_s \simeq 3 \cdot 10^{-47} \text{ cm}^2$ for spin independent interaction of WIMPs with the mass about 50 GeV. However, the number density of remnants in vicinity of Solar system should be by 29 orders of magnitude less, than the number density of these WIMPs, what makes impossible their direct experimental searches.

Taking formally accretion radius for the considered remnants as $r_a = 2Gm_{cr}/v^2$, one obtains $r_a \simeq 10^{-19} \text{ cm}$ for velocity in halo $v \simeq 300 \text{ km/s}$, which is hundreds thousand times smaller, than the size of nuclei. Therefore, penetration of remnants in Solar matter with the number density $n \sim 10^{24} \text{ cm}^{-3}$ cannot lead to a significant effect of accretion, since $n\sigma_a R_{\odot} \approx 2 \cdot 10^{-3}$, where $\sigma_a = \pi r_a^2$ is the accretion cross section and $R_{\odot} \approx 7 \cdot 10^{10} \text{ cm}$ is the Solar radius. Even in neutron stars, with particle number density $n_{ns} \sim 10^{38} \text{ cm}^{-3}$ and radius $R_{ns} \sim 10^6 \text{ cm}$, in which $n_{ns}\sigma_a R_{ns} \approx 3 \cdot 10^6$, the increase of remnant's mass due to accretion $\Delta m = \rho_{ns}\sigma_a R_{ns} \approx 3 \cdot 10^{-18} \text{ g}$ is much less than the mass of the remnant, so that the corresponding decrease of velocity is negligible, what prevents their capture.

The situation can change drastically, if we take into account that the regular remnant is a compact object with the GUT false vacuum interior, in which baryon and lepton numbers are not conserved. It may lead to gravitational capture of proton that induces proton decay, similar to Callan-Rubakov effect in the case of GUT magnetic monopoles [59, 60]. However, on the contrary to the case of magnetic monopoles due to much larger mass of remnants, their number density in the vicinity of the Solar system is too small to have a hope to observe this effect. Indeed, if we take the the cross section of induced proton decay due to its gravitational capture by remnants as $\sigma_a = \pi r_a^2 \approx 3 \cdot 10^{-38} \text{ cm}^2$ and assume that remnants saturate the dark matter density with local number density $n_r \approx 10^{-26} \text{ cm}^{-3}$ in the ton of matter of an underground detector one should expect one event per $10^{26} \text{ s} \approx 3 \cdot 10^{18} \text{ years}$.

As the extreme case, which needs special study in the framework of e.g. bag models, the very penetration of remnant inside the nucleon may induce its decay. But even if the corresponding cross section is determined by the geometrical size of nucleon ($\sigma_i \sim 10^{-26} \text{ cm}^2$) one can expect no more than one event per 10^7 years in one ton of an underground detector. In the matter of a 1 km^3 detector, like IceCUBE, there should be up to 300 events per year. However, the problem of distinguishing such events, in which only 1 GeV energy is released, is crucial in this case.

If induced nucleon decay can take place during penetration of remnant through the neutron star, the remnant is not captured but crosses the star leaving a pin-hole of decayed neutrons in it. This picture is essentially different from the case of much more massive PBHs, whose capture by neutron stars was constrained by [61]. For the induced decay $n \rightarrow \pi^0 + \nu$ about half of the neutron rest energy is released in a nuclear size area owing to π^0 interaction with the neutron star matter, since the timescale of this interaction is much less, than the lifetime of π^0 , τ_0 , $t_i \sim (n_{ns}\sigma_{\pi n}v)^{-1} \sim 10^{-22} \text{ s} \ll \tau_0$. The corresponding pressure can exceed the gravitational pressure and the matter of the neutron star can be ejected in the form of a very narrow collimated jet. Such jets, corresponding to the crossing of remnants through a neutron star can appear at the rate $n_r\pi R_{ns}v \sim 10^{-6} \text{ s}^{-1}$, i.e. about 30 per year per neutron star.

Graviatoms with de Sitter interior can contribute to composite dark matter whose observational signatures are related to electromagnetic radiation which bears information about their interior structure, in particular about the fundamental symmetry scale responsible for de Sitter vacuum interior [35]. Current experiments allow detection of photons up to $10^{11.5} \text{ GeV}$ ([62] and references therein). Present observational possibilities prefer thus graviatoms with the GUT scale interior although those with the Planck scale interior can exist in principle, and probabilities of their production in a collapse are bigger, but their typical frequency, $\hbar\omega \simeq 0.7 \times 10^{19} \text{ GeV}$ is far from the today observational range.

For the charged remnants one can expect also much stronger effect of falling down its center and correspondingly much stronger effect of induced proton decay. If the corresponding cross section is of the same order, as in the case of magnetic monopole $\sigma_i \sim 10^{-28} \text{ cm}^2$, one should expect about 3 events per year of 1 GeV energy release due to slow penetrating massive particles in IceCUBE. Search for this effect needs special study in the analysis of the IceCUBE data.

Let us emphasize that graviatoms are bound states of a remnant with false vacuum interior and an electrically charged particle, captured by it. Therefore one may expect that the remnant component of graviatom can induce nucleon decay, while the charged component provides the enhancement of the corresponding cross section. It makes the searches for graviatoms challenging for IceCUBE experiment.

4 Conclusions

Regular primordial black holes and gravitational solitons with de Sitter vacuum interior can arise in the early Universe from primordial inhomogeneities in assumption that quantum collapse of primordial overdense regions stops at a certain stage when the pressure becomes $p = -\rho$ as a result of symmetry restoration or existence of the limiting density/curvature scale. Evaporation of RPBH leaves behind stable remnants with zero temperature and positive specific heat. They can be considered as heavy dark matter candidates whose observational signatures can serve as signatures for inhomogeneity of the early Universe. RPBH, their remnants and solitons can form graviatoms by capturing available charged particles. Radiation of graviatoms can bear information on the scale of the interior de Sitter vacuum. In the case of the GUT scale interior, radiation of the oscillatory type falls within the ultra-high energy range available in principle for today observational possibilities.

The mass of RPBH remnants is about $10^2 - 10^3 \text{ kg}$, what makes strongly suppressed their gravitational cross section, so they are elusive dark matter candidates, although not as elusive as Planck mass remnants. We have shown that for the remnants with GUT vacuum interior induced proton or neutron decay is possible. The corresponding cross section is strongly en-

hanced for electrically charged graviatoms, making their search as heavy dark matter candidates challenging in the IceCUBE experiment.

Acknowledgment

The work by I.D. was partly supported by the National Science Center of Poland through the grant 5828/B/H03/2011/40. The work by M.Kh. on initial cosmological conditions was supported by the Ministry of Education and Science of Russian Federation, project 3.472.2014/K and his work on the forms of dark matter was supported by grant RFBR 14-22-03048.

References

- [1] A. Zhitnisky, Phys. Rev. **D 74** (2006) 043515.
- [2] M.Yu. Khlopov, Mod. Phys. Lett. **A 26** (2011) 2823.
- [3] J.H. MacGibbon, Nature **329** (1987) 308.
- [4] E. J. Copeland et al, Phys. Rev. **D 49** (1994) 6410.
- [5] B. J. Carr, Proc. of 22nd Texas Symp., ECONFCO **41213** (2004) 0204; astro-ph/0504034.
- [6] L. Bergstrom, the plenary talk at the "Invisible Universe International Conference", Paris, France, June-July 2009, in *AIP Proceedings Series* (2010).
- [7] A.G. Polnarev, M. Y. Khlopov, Sov.Phys.Usp. **28** (1985) 213.
- [8] M. Y. Khlopov, Res. Astron. Astrophys. **10** (2010) 495 [arXiv:0801.0116 [astro-ph]].
- [9] S. Capozziello, G. Cristofano, M. De Laurentis, Eur. Phys.J. **C 69** (2010) 293.
- [10] Ya.B. Zeldovich and I.D. Novikov, Sov. Astron. **10** (1967) 602.
- [11] S.W. Hawking, Mon. Not. R. Astron. Soc. **152** (1971) 75.
- [12] D. H. Lyth and A. Riotto, Phys. Rep. **314** (1999) 1.
- [13] F. Scardigli, C. Gruber and P. Chen, Phys. Rev. **D 83** (2011) 063507.
- [14] K. Nozari and S.H. Mehdipour, Mod. Phys. Lett. **A 20** (2005) 2937.
- [15] S. Dimopoulos and G. Landsberg, Phys. Rev. Lett. **87** (2001) 161602.
- [16] B. Koch, M. Bleicher and S. Hossenfelder, JHEP **0510** (2005) 053.
- [17] H. Stoecker, Int. J. Mod. Phys. **D 16** (2007) 185.
- [18] L. Bellagamba, R. Casadio, R. Di Sipio, V. Viventi, arXiv:1201.3208 [hep-ph] 26 Mar 2012.
- [19] G.C. Nayak, Phys. Part. Nucl. Lett. **8** (2011) 337.
- [20] G. Landsberg, J. Phys. **G 32** (2006) R337.

- [21] C.M. Harris, M.J. Palmer, M.A. Parker, P. Richardson, A. Sabetfakhri, B.R. Webber, *JHEP* **0505** (2005) 053.
- [22] A. Casanova and E. Spallucci, *Class. Quant. Grav.* **23** (2006) R45.
- [23] R.J. Adler, P. Chen and D.I. Santiago, *Gen. Rel. Grav.* **33** (2001) 2101.
- [24] M. Maziashvili, *Phys. Lett. B* **635** (2006) 232.
- [25] K. Banerjee and S. Ghosh, *Phys. Lett. B* **688** (2010) 224.
- [26] George F.R. Ellis, <http://arxiv.org/abs/1310.4771> (2013).
- [27] F.S.N. Lobo, G.J. Olmo and D. Rubiera-Garcia, *JCAP* **07** (2013) 011.
- [28] L. Susskind, *J. Math. Phys.* **36**, 6377 (1995).
- [29] H. Kawai, Y. Matsuo, Y. Yokokura, <http://arxiv.org/abs/1302.4733> (2013).
- [30] I. Dymnikova, the invited talk at the "Invisible Universe International Conference", Paris, France, June-July 2009, in *AIP Proceedings Series* (2010).
- [31] R. Aros, *Phys. Rev. D* **77** (2008) 104013.
- [32] I. Dymnikova, *Int. J. Mod. Phys. D* **5**, 529 (1996).
- [33] I. Dymnikova and E. Galaktionov, *Phys. Lett. B* **645** (2007) 358.
- [34] I. Dymnikova and M. Korpusik, *Phys. Lett. B* **685**, 12 (2010).
- [35] I. Dymnikova and M. Fil'chenkov, *AHEP* **13** (2013) Article ID 746894.
- [36] I.G. Dymnikova, *Gen. Rel. Grav.* **24** (1992) 235.
- [37] I.G. Dymnikova, *Phys. Lett. B* **472** (2000) 33.
- [38] I. Dymnikova, *Class.Quant.Grav.* **19**, 725 (2002).
- [39] I. Dymnikova and E. Galaktionov, *Central European Journal of Physics* **9** (2011) 644.
- [40] K.A. Bronnikov, A. Dobosz and I. Dymnikova, *Class. Quant. Grav.* **20** (2003) 3797.
- [41] K.A. Bronnikov and I. Dymnikova, *Class. Quant. Grav.* **24** (2007) 5803.
- [42] K.A. Bronnikov, I. Dymnikova and E.V. Galaktionov, *Class. Quant. Grav.* **29** (2012) 095025.
- [43] I.Dymnikova and B. Soltyssek, *Gen. Rel. Grav.* **30** (1998) 1775.
- [44] P. Chen, *New Astron. Rev.* **49** (2005) 233.
- [45] K. Nozari, *Astropart. Phys.* **27** (2007) 169.
- [46] G.W. Gibbons and S.W. Hawking, *Phys. Rev. D* **15** (1977) 2738.

- [47] I. Dymnikova and M. Korpusik, Entropy **13** (2011) 1967.
- [48] T. Nakama, T. Harada, A. Polnarev and J. Yokoyama, JCAP **01** (2014) 037.
- [49] I. Dymnikova, in: Internal structure of black holes and spacetime singularities, Eds. M. Burko and A. Ori, Bristol Joint of Physics and the Israel Physical Society (1997) 422.
- [50] E. Poisson and W. Israel, Class. Quant. Grav. **5** (1988) L201.
- [51] V.P. Frolov, M.A. Markov and V.F. Mukhanov, Phys. Rev. **41** (1990) 383.
- [52] D. Boyanovski, H.J. de Vega and D.J. Schwarz, Ann. Rev. Nucl. Part. Sci. **56** (2006) 441.
- [53] R.V. Konoplich, S.G. Rubin, A.S. Sakharov, M.Yu. Khlopov, Phys.Atom.Nucl. **62** (1999) 1593.
- [54] R.V. Konoplich, S.G. Rubin, A.S. Sakharov, M.Yu. Khlopov, Gravitation & Cosmology **6** (2000) 153.
- [55] I.Dymnikova, M.Yu. Khlopov, L. Koziel and S. G. Rubin. Gravitation & Cosmology **6** (2000) 311; e-Print ArXiv: hep-th/0010120.
- [56] O.E. Kalashev, G.I. Rubtsov, and S.V. Troitsky, Phys. Rev. **D 80** (2009) Article ID 103006.
- [57] M. Lemoine, Phys. Lett. B **481** (2000) 333, arXiv:hep-ph/0001238.
- [58] M.Yu.Khlopov, A.Barrau, and J.Grain, Class. Quantum Grav. **23** (2006) 1875, arXiv:astro-ph/0406621.
- [59] C.G. Callan, Nucl. Phys. **B212** (1983) 391.
- [60] V.A. Rubakov, Nucl. Phys. **B203** (1982) 311.
- [61] F. Capela, M. Pshirkov, P. Tinyakov, Phys. Rev. **D 87** (2013) 123524.
- [62] O.E. Kalashev, G.I. Rubtsov, and S.V. Troitsky, Phys. Rev. **D 80** (2009) 103006.